

CORRELATION OF FRACTURE BEHAVIOR WITH MICROSTRUCTURE IN FRICTION STIR WELDED, AND SPIN-FORMED AL-LI 2195 DOMES

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Abstract

Single-piece, spin-formed domes manufactured from friction stir welded (FSW) plates of Al-Li alloy 2195 have the potential to reduce the cost of fabricating cryogenic propellant tanks. Mechanical properties in the completed domes can be related directly to the final material condition and the microstructures developed. However, these new fabrication techniques have resulted in unexpected material challenges, such as abnormal grain growth in the weld nugget and the propensity for fracture in the adjacent thermo-mechanically affected zone (TMAZ). In this study, the microstructure and texture transformations within the TMAZ are related to fracture location in the vicinity of the weldment. The texture variations in the TMAZ are caused primarily by the varying amounts of shear deformation introduced during the FSW process. Grain morphology and microtexture characteristics are examined as a function of location in the TMAZ via electron backscatter diffraction (EBSD). A strong correlation between fracture location and the presence of texture banding in the TMAZ is observed. The fracture path tends to follow a distinct region of low Taylor Factor (TF) grains.

Introduction

Current multi-piece, welded construction of cryogenic tanks for NASA launch vehicles is expensive due to inefficient manufacturing practices. Exploratory techniques, combining friction stir welding and spin forming, have shown promise in the production of the end domes for next generation large-scale, cryogenic tanks [1]. Replacement of conventional Al alloys (2219) with Al-Li alloys (2195) has already reduced structural weight and increased payload capabilities on existing launch vehicles. However, commercially available plates are not large enough for spin forming of a 5-meter diameter, hemispherical dome from a single plate. In the current study, friction stir welding was used to join two plates together to provide a sufficiently large spin forming blank. Friction stir welding is an attractive process because it is already employed in existing tank fabrication due to enhanced mechanical property retention (vs. fusion welding). The defect-free, fine-grained FSW microstructure also provides better warm formability compared to conventional welds.

The welded 2195 blank was spin-formed in the O temper condition to maximize formability and then post-fabrication heat treated to the T8 temper to meet service properties. However, during tensile testing some specimens fractured in the vicinity of the TMAZ/weld nugget interface, rather than the desired location within the weld nugget. The transition between the plate and weld nugget microstructure is expected to have a strong influence on fracture

behavior in the TMAZ. A detailed characterization of the microstructure was undertaken to explain this behavior.

In this study, EBSD analysis was used to evaluate a tensile specimen loaded in TD, which failed in the TMAZ on the advancing side (AS) of the weldment. This tensile specimen was taken from the rim of a fully formed dome. The rim region experienced ~25% warm deformation during spin forming and an additional 1.5% cold stretch prior to ageing. EBSD analyses offer a convenient way to quantify location-dependent changes in microstructure and texture from the base material (BM) toward the AS TMAZ/weld nugget interface. Changes in microtexture, in terms of deformation-, recrystallization-, and shear-type components, may be correlated with location-dependent variations in deformation during welding. Localized crystallographic rotations will produce texture transformations, and the physical rotation of grains inherent in the FSW process will create a short-transverse loading state near the AS TMAZ/weld nugget interface. This stress state is considered to be a prime reason for poor S-T fracture toughness in Al-Li alloy wrought products [2]. These alloys exhibit strong texture and lamellar microstructures in the as-rolled condition, i.e. the constituent grains are very thin, and highly elongated. The combination of these factors results in greater mechanical anisotropy than conventional Al alloys. Texture controls strength and governs anisotropy, and the grain morphology influences ductility, toughness, and fracture behavior. Thus, quantification of the microstructural variations may reveal factors that promote failure in the AS TMAZ region.

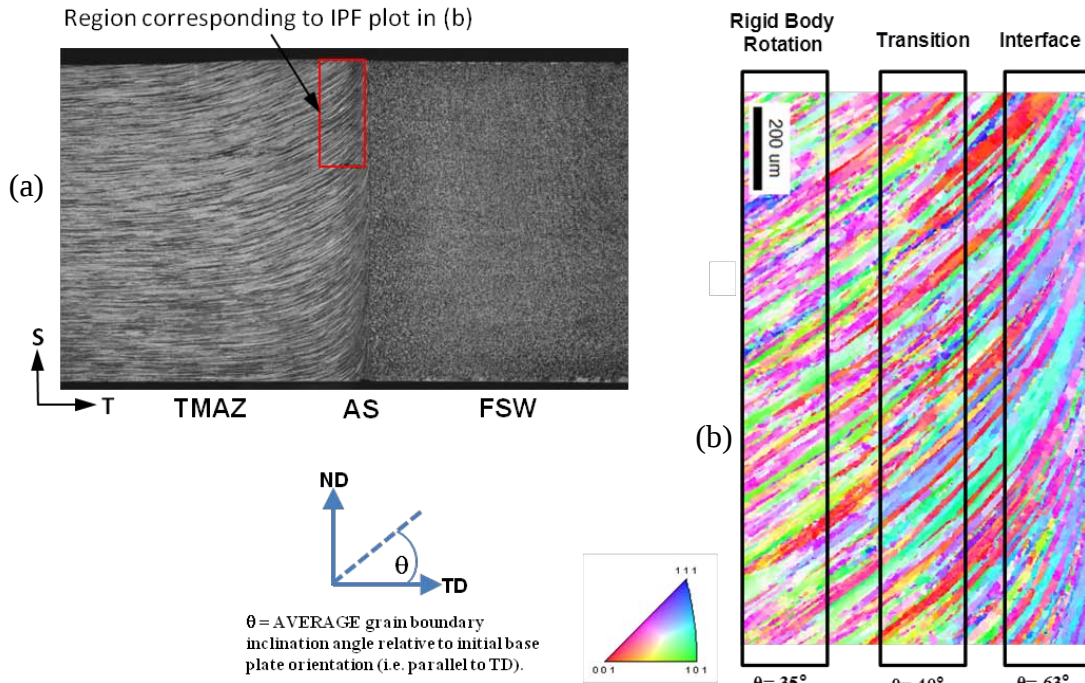


Figure 1. Typical FSW/TMAZ morphology (a) and IPF plot of crystal directions parallel to ND (b) for the highlighted AS TMAZ region.

Experimental Procedures

EBSD investigations were conducted on an intact weld section taken from near the tensile specimen location. The sample was sectioned normal to the weld direction (L or RD) to enable evaluation of the cross-section through the weld (T-S or TD-ND plane) as illustrated in

Figure 1(a). After sectioning, the sample was mechanically polished. EBSD scans were generally conducted at 500x magnification and a step size of 1 μm . Multiple scans were collected for each sample to provide through-thickness data in the region of interest, i.e. the AS of the TMAZ. The orientation data collected was rotated back to coincidence with the standard plate axes to establish a common frame of reference. This permitted more direct correlation between texture variations in the sample with the texture characteristics of the initial BM. The microtexture data compiled was analyzed via pole figures (PF), inverse pole figures (IPF), and TF plots. TF's are a scaling factor which relates the resolved shear stress to the yield strength based on the geometric alignment of slip systems relative to a specified loading axis [3].

Results and Discussion

The series of conventional PF's shown in Figure 2 aids in visualizing the transition in texture across the partitioned regions shown in Figure 1(b). The "Base Plate" column portrays a typical rolled Al-Li alloy texture representative of the BM. The next three columns correspond to the three partitioned regions noted in Figure 1(b) which are based on proximity to weld interface. These regions have been named to reflect their distinct texture characteristics – "Rigid Body Rotation", "Transition", and "Interface." The final column labeled as "Rotated Interface" is the texture from the "Interface" region, with additional rotations applied for alignment with conventional shear texture. The development of a shear texture within the weld nugget is well-documented for FSW products, and generally requires some rotation to align it with the ideal shear texture [4]. Physical rotations of the shear plane normal and shear direction relative to the plate reference frame are a direct result of material flow, shoulder effects, and/or tool geometry.

The evolution of texture from BM to the AS TMAZ/weld nugget interface is evident by comparison of the PF plots from left to right in Figure 2. The first region labeled "Rigid Body Rotation" is characterized as a region where the texture of the BM experienced primarily a rigid body rotation about the weld direction (RD), which is attributed to the upward flow of material, as evidenced in Figure 1(b) by the physical bending of the grains [5]. Nominally, it retains the same symmetry and distribution as the base plate PF representation of the texture, giving the appearance that the PF is rotated in a rigid body manner (or shifted horizontally in the PF plot).

The next region, labeled "Transition," exhibits a breakup of the initial BM symmetry and orientation into an atypical texture. The features may be best described as an intimate mixture of the BM and weld nugget textures. Significant rotations about ND are observed which are associated with material flow around the tool axis, giving rise to the disruption of the BM texture. This in-between region did not exhibit any characteristics that could be easily linked with known texture patterns. Lastly, the region labeled "Interface" lies within approximately 200 μm of the distinct TMAZ/weld nugget interface. In this region, the texture strongly resembles the shear texture typically observed in the dynamically recrystallized nugget microstructure. However, this texture does appear slightly skewed with respect to the ideal simple shear texture.

Figure 3(a) shows the texture from the through-thickness scans in the form of an inverse pole figure plot; (b) the Taylor factor plot for tension in TD; and (c) the failed cross-section from a tensile specimen near the same region. The texture adjacent to the AS interface has a high propensity for $\langle 011 \rangle$ and $\langle 001 \rangle$ crystal directions parallel to RD (i.e. in the [100] IPF plot). These components would be associated with shear and recrystallization (Cube-type) components, respectively. The contribution of rolling-type orientations to the overall texture increases with

distance from the TMAZ/nugget interface. This texture would be associated with the blue region of the stereographic triangle for the [100] IPF, or the $\langle 101 \rangle$ region of the [001] IPF plot.

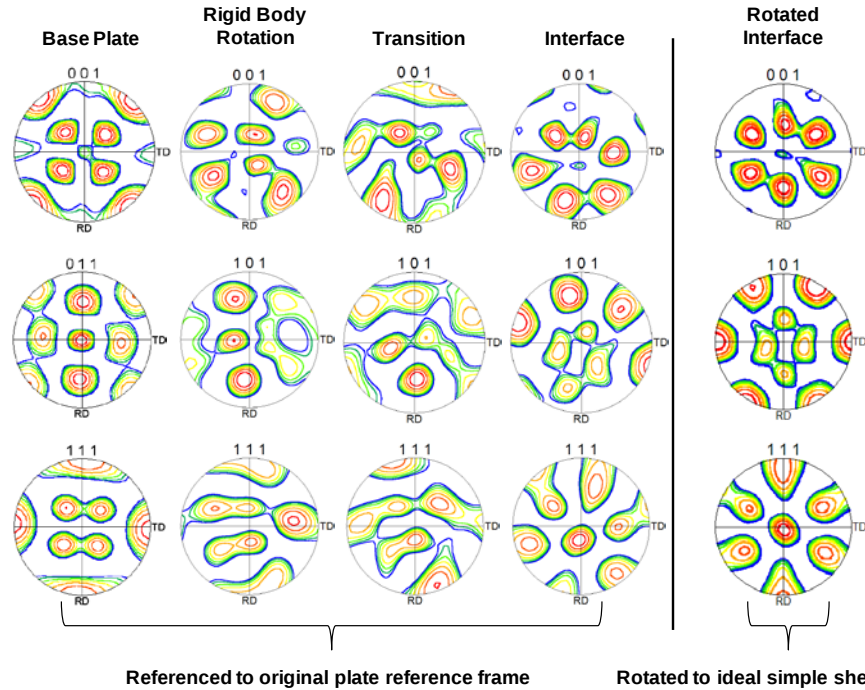


Figure 2. Pole figures from several sequential regions illustrating the transition in texture from base metal to the weld nugget interface along the advancing side.

In addition to characterizing the texture evolution, grain specific TF's were used to assess the crystallographic strength distribution in the TMAZ. Low-TF grains are associated with a lower flow stress (softer), while high-TF grains are crystallographically harder [3]. The TF plot reveals a vertical "band" of low-TF grains (blue) in close proximity to the AS TMAZ/weld interface. The low-TF band was found to start approximately 75 μm from the interface and was roughly 400 μm wide. The location of fracture shown in Figure 3(c) was approximately 150 μm from the interface and the fracture path was approximately 400 μm wide. It is readily apparent that there is a correlation between fracture location and a band of low-TF grains adjacent to the AS interface.

The low-TF band occurs in the region of texture transition in the IPF plot; i.e., where the orientation is rotating from $\langle 111 \rangle$ towards $\langle 011 \rangle$ - and $\langle 001 \rangle$ -type orientations ($\parallel$ to RD). A similar type of transition is also observed over the same region in both the [001] and [010] IPF plots. This corresponds to the region within the TMAZ labeled as the "Transition." The band of low-TF grains signifies a crystallographically weaker zone within the TMAZ. In addition, the pairing of high-TF (red) and low-TF (blue) grains likely contributes to the observed intergranular (delamination) failure. This tendency arises due to increased stress concentrations which develop as a result of a "hard" (high-TF) grain adjacent to a "soft" (low-TF) grain as strain transfer is difficult between these two dissimilar orientations [6]. In comparison with the fracture image, the TF plot shows a strong correlation between the failure location and a microstructural region susceptible to strain localization and delamination fracture. The tendency for delamination fracture may be further magnified by the S-T loading state created by the 'upturned' grain boundaries.

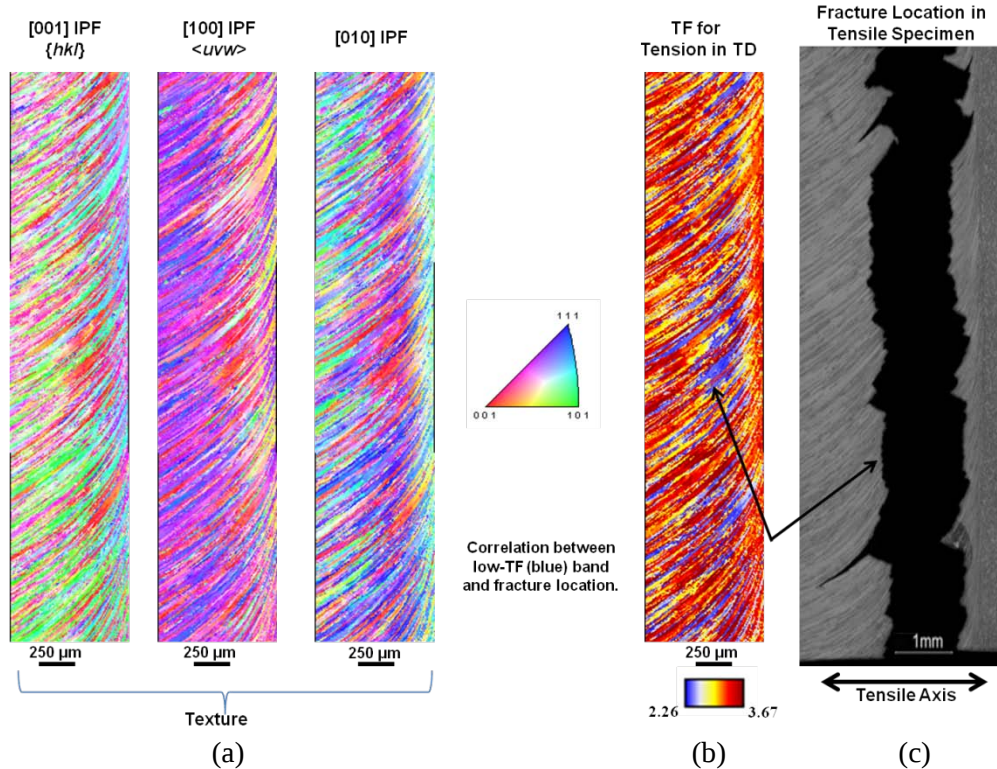


Figure 3. EBSD data from AS TMAZ/weld nugget interface; (a) IPF plots; (b) TF plot for uniaxial tension in TD; and (c) cross section from failed tensile specimen loaded in TD.

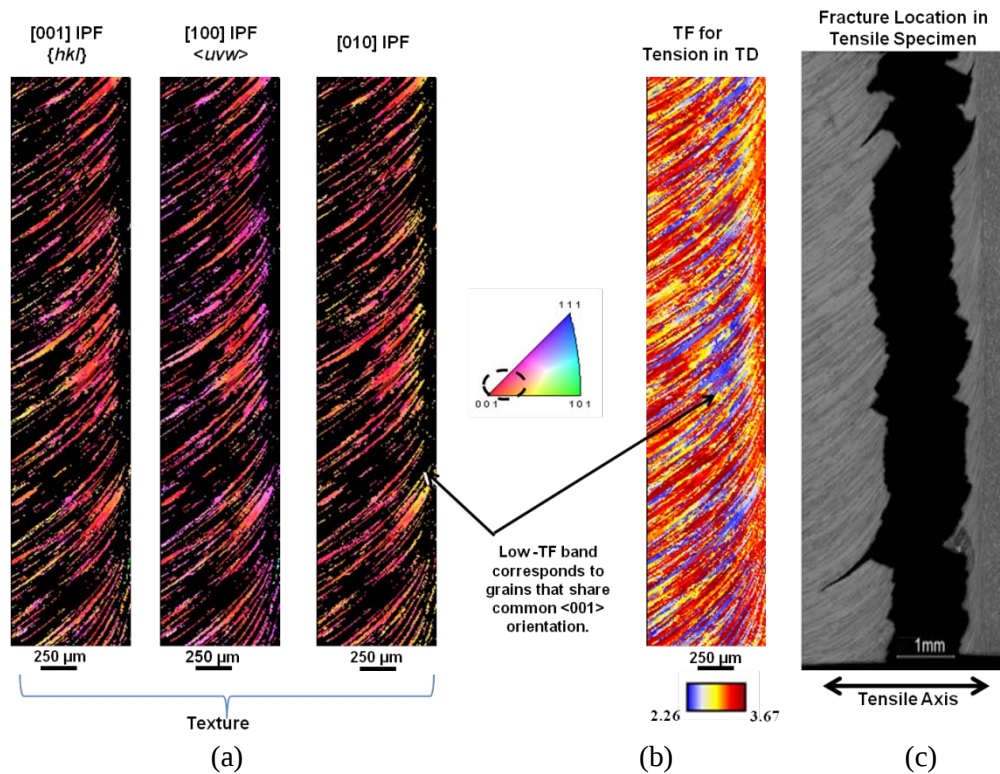


Figure 4. Partition of low-TF grains (TF < 2.6) from Figure 3.

TF values are dependent on crystallographic orientation in general, hence there is high probability that the low-TF grains coincide with a specific type of texture. Thus, the IPF plots from Figure 3 have been partitioned to show only the low-TF grains (TF < 2.6) in Figure 4. All grains with a TF above 2.6 appear black. By considering only the low-TF grains, the IPF plots reveal a strong preference for <001> grains parallel to [001] and [100] being confined to the low-TF band. This represents a common recrystallization component in Al alloys, namely the {001}<100>, Cube orientation. Further study is needed to confirm whether this recrystallization resulted from FSW or solution heat treatment, and determine the influence of the deformation associated with the spin forming.

Conclusions

The impact of the FSW process on material flow and resultant texture variations in the TMAZ can be correlated with both physical and crystallographic rotations. The upward flow of material produces an initial rigid body rotation of the BM microstructure about the weld direction (RD) which is both physical and crystallographic in nature. Further into the TMAZ, more pronounced crystallographic rotations (about ND) promote fragmentation of the BM texture, leading to a region of transitional texture. Ultimately, a strong shear texture is formed immediately adjacent to the weld interface as a result of the shear deformation inherent to the FSW process.

This study reveals a striking correlation between microtexture and fracture location in a friction stir welded and spin-formed Al-Li wrought material. The location of fracture can be linked with highly localized variations in crystallographic texture, and the resultant variation in TF. The emergence of a Cube, recrystallization texture in the TMAZ close to the AS interface creates an area of weaker texture intensity, i.e. a band of low-TF grains for loading in TD. The location of this region within the TMAZ was observed to be coincident with the fracture path. In addition, the occurrence of intergranular fracture is likely along boundaries between low-TF and high-TF grains due to local strain incompatibility. While there are additional microstructural factors to be considered in relation to the failure, these findings suggest that local texture promoted fracture in the vicinity of the AS interface.

References

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